GeoResJ 6 (2015) 30–43

Contents lists available at ScienceDirect

GeoResJ

journal homepage: www.elsevier.com/locate/GRJ

Maximizing the value of historical bedrock field observations: An example from northwest Canada

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ARTICLE INFO

Article history:
Received 1 October 2014
Revised 22 January 2015
Accepted 23 January 2015
Available online 14 March 2015

Keywords:
Data rescue
Bedrock mapping
Historical data
GIS data
Operation Norman
Canada

ABSTRACT

Historical bedrock field observations have potential for significant value to the scientific community and the public if they can be rescued from physical records stored in archives of scientific research institutions. A set of historical records from 'Operation Norman', a bedrock mapping activity conducted in northwestern Canada by the Geological Survey of Canada (GSC) from 1968 to 1970, was identified as suitable for data rescue and incorporation into a GIS geodatabase. These observational data, including field stations, lithology descriptions, structural measurements, measured section locations, and fossil localities, were digitized as geospatial features with attributes assigned according to the observation records. Over 90% of the original observations were successfully rescued in this manner, allowing for effective incorporation with newer observations. Lack of reliable location information for field observations was the primary impediment to effective data rescue. Access to original participants in Operation Norman was particularly helpful in ensuring successful data rescue, as was the excellent state in which research materials had been curated. The resulting dataset of combined historical and recent observations provides improved distribution of observations to constrain geological analysis and map interpretation. Rescued data from Operation Norman have been incorporated in new bedrock map compilations and other scientific publications.

1. Introduction

Since its founding in 1842, the Geological Survey of Canada (GSC) has been Canada's main federal government agency for geoscience surveys, research, and information, and has accumulated an immense amount of information about the Canadian landmass. Current objectives of the GSC emphasize the importance of providing public geoscience knowledge. In its most recent formulation [1; p. 2], the GSC's mission is to "[p]rovide public geoscience knowledge to sustain the exploration effectiveness and international competitiveness of the mineral and energy sectors, inform the stewardship of [Canada's] onshore and offshore lands, and increase the safety and security of Canadians". This emphasis on the provision of public data is in keeping with the recent Government of Canada Open Data initiative (see http://data.gc.ca/eng/open-data). However, although much GSC data and information is available publicly in hardcopy and digital publication formats, many of the original observation records remain in GSC archives where they are relatively inaccessible to the public. This is particularly true of data from historical field studies.

There are two key principals of open data initiatives that strongly encourage data rescue efforts: completeness and machine readability (see http://data.gc.ca/eng/open-data-principles). Indeed, both principles are explicitly referenced in a commonly used definition of data rescue (emphasis added): "an ongoing process of **preserving all data** at risk of being lost due to deterioration of the medium, and the digitizing of current and past data into **computer-compatible form for easy access**" [2]. Traditional, hardcopy bedrock maps published by the GSC fulfill neither of these principles. Although such maps were based on extensive field observations, only an incomplete subset of data could be displayed on the published map or included in an accompanying report. Hardcopy data and information, such as that preserved for many historical GSC research activities, is not machine readable and thus is of suboptimal value because the data and interpretations are not easily integrated with other data sources for continued research. The push to make data and interpretations more widely available in usable formats has encouraged the GSC to modernize its data collection and map delivery techniques, including strategies for incorporating

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http://dx.doi.org/10.1016/j.grj.2015.01.004
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historical data—for the sake of completeness—into new publications in modern, machine-readable formats.

This paper describes an effort to rescue archived data from Operation Norman, a GSC bedrock-mapping program carried out between 1968 and 1970. Although these data were well organized and relatively safe from loss, the data rescue mission we describe has given them a second life in the public domain and improved their analytical value by reproducing them in modern GIS format.

2. Historical background

2.1. Operation Norman (1968–1970)

In 1952, the GSC began to use helicopters in support of its bedrock mapping activities. This resulted in a series of regionally extensive reconnaissance operations, each named for the geographic region in which it was undertaken [3]. By the late 1960s, only one large sedimentary terrain remained in Canada that lacked geological map coverage at 1:500,000 scale. This was a region of about 375,000 km^2 on Canada's northern mainland (Fig. 1), delineated by a southern boundary at 64° N, a western boundary at 132° W, a northern boundary at the shore of the Arctic Ocean, and an eastern boundary defined by the contact between Paleozoic strata of the Interior Platform and underlying Precambrian rocks of the Canadian Shield [22]. It encompassed parts of the Mackenzie Mountains, Mackenzie Plain (including the long-producing oil field at Norman Wells), Franklin Mountains, and Interior Plains. Operation Norman was undertaken to address this lack, and was staffed mainly by scientists from the GSC's Calgary office.

Primary field operations for Operation Norman were carried out during the summer field seasons of 1968, 1969, and 1970, and included bedrock mapping, stratigraphic studies, and investigation of surficial deposits [23–25]. Bedrock mapping was done at reconnaissance scale, using standardized field-note forms, cross-referenced to localities marked on aerial photographs and/or topographic maps (Fig. 2).

Following map compilation, bedrock maps were published in a variety of formats (Fig. 1), at scales dictated by the level of geological detail [23]. Some, e.g. [13,20,21] were prepared to the standard of what were termed "A series" maps—multicoloured, professionally drafted and edited maps that presented "an author's considered conclusions on the geology of an area" [26, p. 1]. These maps were published at 1:250,000 scale, and some were issued with accompanying "Memoirs", a publication series that was intended to present comprehensive final reports on the geology of specific areas [26]. Memoirs, at minimum, included detailed information on the character of and variation within geological units, as well the structural geology of the study area, e.g. [27]. Maps compiled at 1:500,000 scale generally were published as "Preliminary Maps", which were professionally drafted and incorporated colour line-work but did not utilize

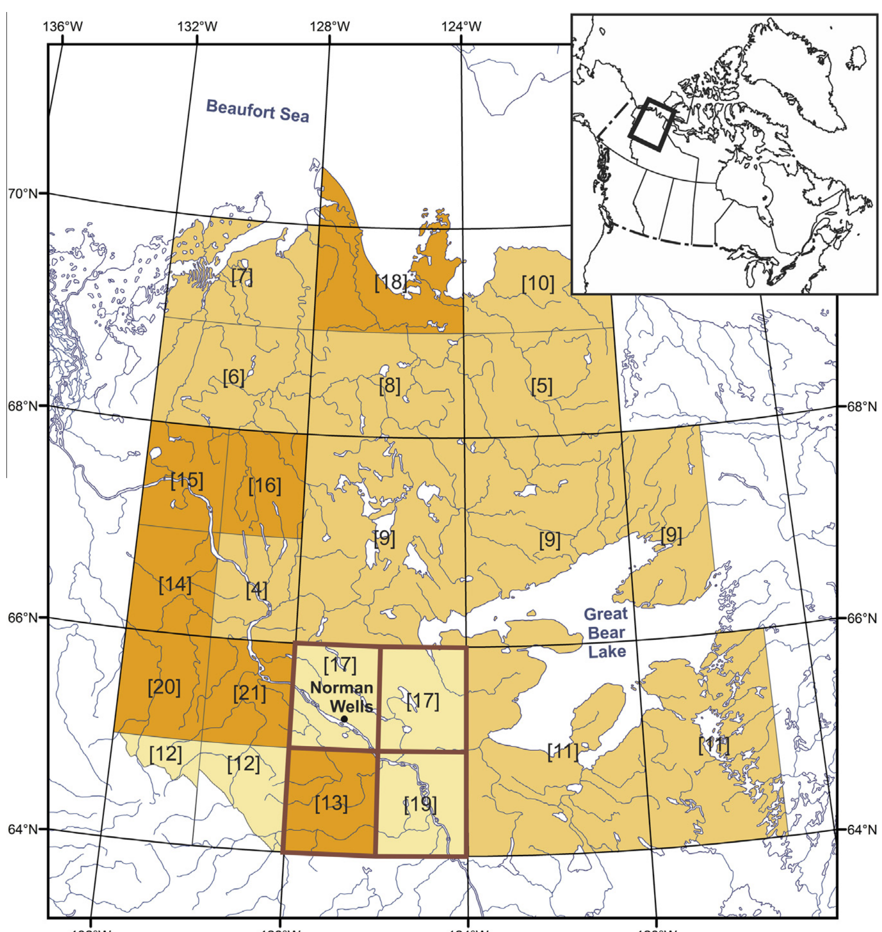


Fig. 1. Location map. Coloured area on main map is the region covered by Operation Norman (1968–1970); dark orange areas were published as GSC A-series maps, medium orange areas as GSC Preliminary maps, and light orange as GSC Open File maps (see Section 2.1). Numbers correspond to Operation Norman map publications [4–21]; see reference list. Map areas with heavy dark orange outline were included in the data rescue activity documented in his paper. Inset shows position of detailed map in northwestern Canada. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

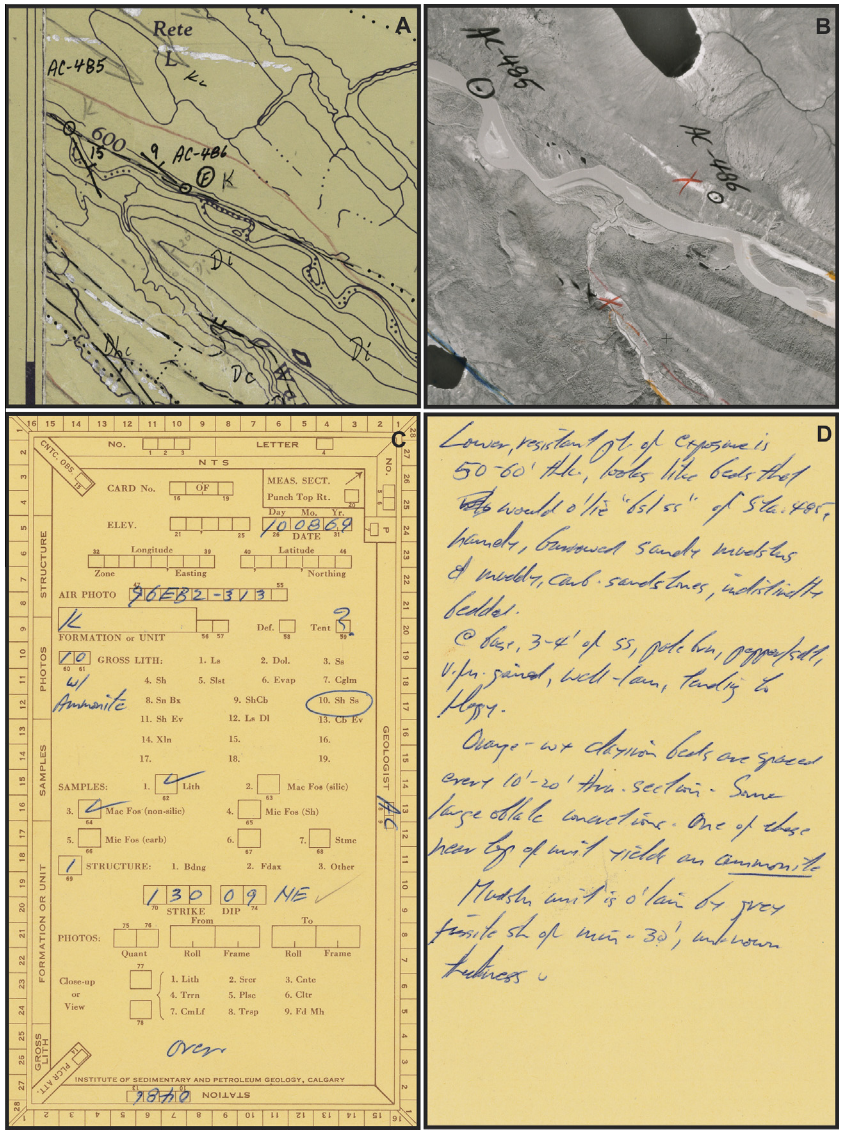


Fig. 2. Operation Norman field observation records. (A) Portion of a field map showing station locations and some interpretation. (B) Air photo corresponding to west-central part of (A), showing how stations were marked and labeled. (C) Station observation card for station 69AC486 (location shown in A and B), showing the systematic organization of basic observations and metadata. (D) Freestyle notes for station 69AC486, written on the back of the observation card shown in Fig. 2C.

colour fills to indicate geological units, e.g. [11]. Such maps commonly were accompanied by "Papers", brief reports including descriptions of geological units and summaries of structural features, e.g. [28]. A final group of maps were published as "Open File" releases, the most informal publication series of the Geological Survey of Canada. At the time of Operation Norman, these consisted of the authors' hand-drawn, hand-lettered map compilations, with little or no input from professional cartographers, e.g. [12,17,19]. Geological descriptions were limited to brief unit summaries and basic information about line and point features, presented in the map legends. Publication technology of the time generally precluded inclusion of data at the level of individual outcrops in even the most detailed maps and reports, although partial outcrop descriptions were sometimes included in the texts of reports, for example to illustrate regional variations within map units, e.g. [27].

GSC Memoirs and GSC Papers published with Operation Norman maps generally did not include measured stratigraphic sections. Instead, measured sections were published in thematic reports that commonly focused on a specific stratigraphic interval, e.g. [22,29].

2.2. Geo-mapping for Energy and Minerals Program (2008–2013)

In 2008, it was announced that the GSC would undertake the Geo-mapping for Energy and Minerals (GEM) Program. The GEM Program was to have a budget of $100 million over 5 years, to provide modern, regional-scale geological knowledge for northern Canada. The GEM Program was divided into a number of projects, including several focused on energy resources. The Mackenzie Delta and Corridor Project [30,31], hereafter referred to as "the Project", focused on hydrocarbon potential in a region that overlapped geographically with the study area of Operation Norman. A key goal of the Project was to produce modern, GIS-enabled bedrock geology maps for the region around the Norman Wells oil field, as an aid to hydrocarbon exploration and land-use planning decisions (Fig. 1). The map areas in question corresponded to areas published by Operation Norman geologists as three Open File maps and one A-series map [17,19,13]. In terms of Canada's National Topographic System (NTS), the maps involved are the western half of NTS 96C, and all of NTS 96D, E, and F.

At the outset of the Project, we were aware that the scientists of Operation Norman had organized their field data carefully and

FEATURE	station (B)
SUBFEATURE	visited outcrop
STATION_ID	69AC486
PHYS_ENV	slope
OC_QUALITY	
OC_SIZE	25-30 m thick
MAP_UNIT	Cretaceous
OBSERVER	Jim Aitken
AIRPHOTO	A12590-313
OBS_DATE	1969-08-10
REMARKS	overlies sandstone of 69AC485
SINCE_LAST	
LOC_METHOD	georeferenced image
LATITUDE	65.369199
LONGITUDE	-127.933855
GEO_DATUM	NAD83
ELEVATION	208
VERT_DATUM	WGS84
ELEV_METH	50k DEM
SOURCE_REF	Operation Norman, 1968-1970
MAP_ID	96E/SW

FEATURE	lithology	lithology (C)
STATION_ID	69AC486	69AC486
LITH_ID	69AC486a	69AC486b
OCCURRENCE	bed	
LITHGROUP	sedimentary	
LITHDETAIL	mudstone	
MAP_UNIT	Cretaceous	
COMP_QUAL	carbonaceous	
TEXT_QUAL	sandy	
STRUC_QUAL	bioturbated, indistinctly bedde	
MINERALS		
GR_SIZE_MN		
GR_SIZE_MX		
FR_COLOUR		
W_COLOUR		
BEDDING_MN		
BEDDING_MX		
FOSSILS	ammonite	
FOS_NOTES	found in concretion	
REMARKS	lower, resistant part of exposure	at base of exposure, 3-4 feet
SOURCE_REF	Operation Norman, 1968-1970	Operation Norman, 1968-1970

FEATURE	planar orientation measurement (D)
PLANAR_ID	69AC486a01
SUBFEATURE	bedding
ATTITUDE	upright
YOUNG_EVID	evidence unknown, historical data
GENERATION	primary
METHOD	measured at station
DIP_DIR	40
STRIKE	310
DIP	9
LITH_ID	69AC486a
STATION_ID	69AC486
LINEAR_ID	
REMARKS	recorded as 130/09 NE
SOURCE_REF	Operation Norman, 1968-1970
MAP_ID	96E/SW

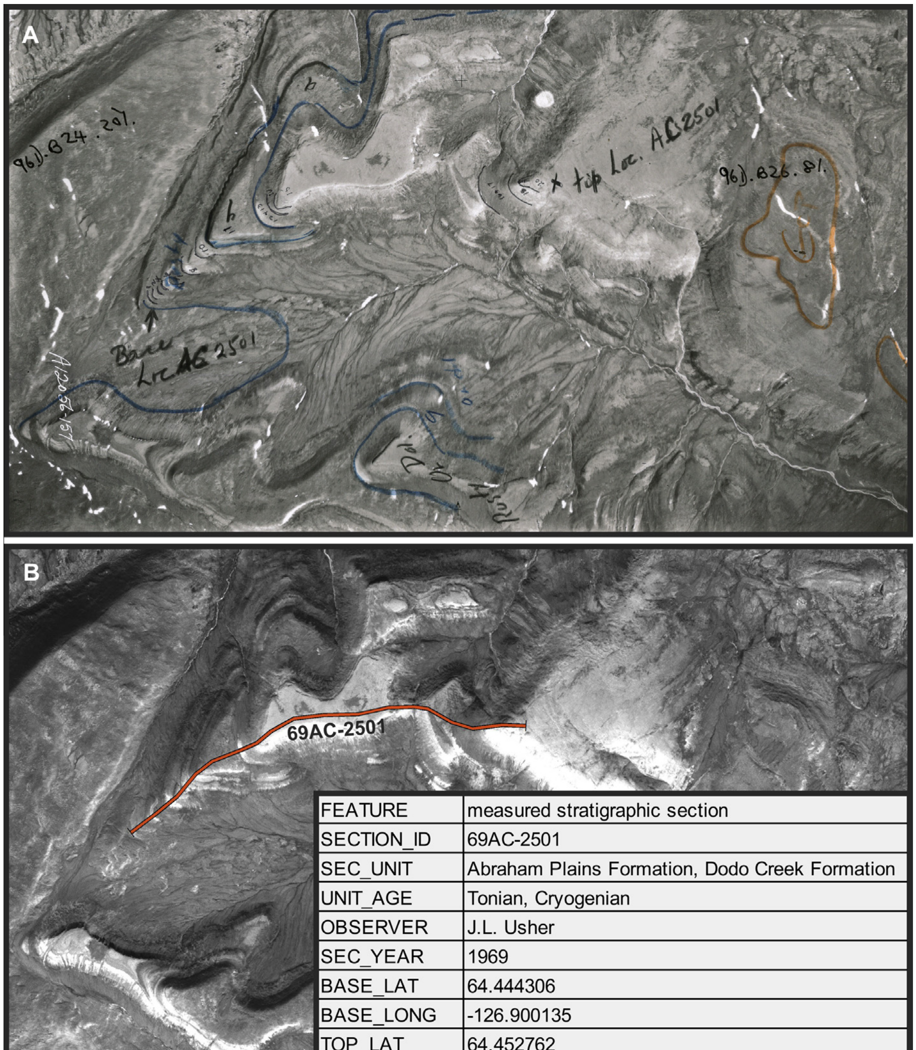
Fig. 3. GIS representation of archival station 69AC486; compare with analog representation in Fig. 2. (A) Location of station shown on georeferenced satellite imagery. (B) Properties showing the basic information about the station, as recorded in project geodatabase. (C) Lithology description from the station. (D) Bedding measurement from the station. Note the use of the STATION_ID (outlined in bold) in each record to link all the information together.

stored these materials at the GSC's Calgary office, where we work. This presented an obvious opportunity for data rescue, whereby data from Operation Norman could be transferred from hard-copy formats into the Project's geodatabase.

3. Data rescue workflow

3.1. Materials and staff requirements

As a result of good record-keeping practices by the scientists who participated in Operation Norman, records preserved by the GSC from that operation include the original geological observations, as well as metadata about those observations, such as the location, date, and observing geologist. Those records were preserved as: field notes recorded on structured observation cards; paper field maps with station locations indicated; air photos with station and measured section locations; published map compilations; measured section field notes, ranging from general summaries of map units to detailed descriptions at the metre scale; and scanned copies of GSC internal paleontological reports. This material was preserved in an organized manner and in safe storage to minimize degradation of the physical material over time. The presence of field maps and air photos with location information that could be tied to observations in the field notes (Fig. 2) opened up the possibility of creating GIS records of these observations. The materials required to transfer Operation Norman observations into GIS records included: a drum scanner to scan original map manuscripts; ArcGIS™ software (desktop version 9.3.1) from ESRI®; georeferenced visible spectrum satellite imagery; and topographic base map data files provided by Geomatics Canada (available from the GeoGratis website of Natural Resources Canada (NRCan), http://geogratis.gc.ca/geogratis/Home?lang=en).



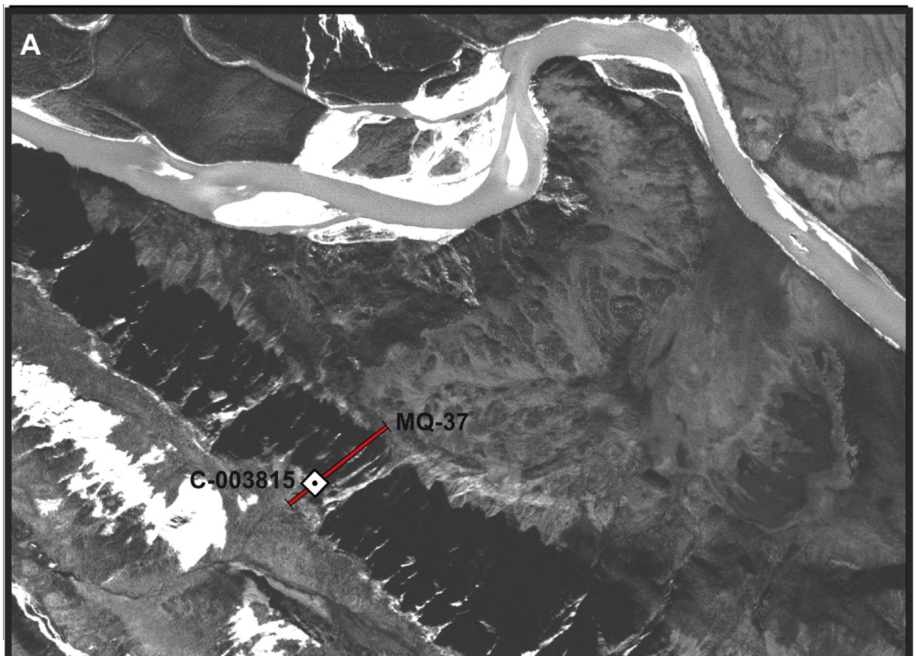
FEATURE	measured stratigraphic section
SECTION_ID	69AC-2501
SEC_UNIT	Abraham Plains Formation, Dodo Creek Formation
UNIT_AGE	Tonian, Cryogenian
OBSERVER	J.L. Usher
SEC_YEAR	1969
BASE_LAT	64.444306
BASE_LONG	-126.900135
TOP_LAT	64.452762
TOP_LONG	-126.833415
GEO_DATUM	NAD83
CONFIDENCE	defined
LOC_REMARK	location transferred from airphoto trace
SOURCE_REF	J.L. Usher, unpublished data
MAP_ID	96D/SE
SHAPE_LEN	3586.8

Fig. 4. Representations of archival measured section 69AC-2501. (A) Hand-annotated Operation Norman air photo; base and top of section are marked, along with some interval boundaries. (B) GIS representation of the section as a path on a georeferenced satellite image, with route of section as inferred from the air photo record. Also shown are associated properties as recorded in the project geodatabase.

In addition to the material requirements noted above, the data rescue process required the time and effort of three junior scientists, employed in both full-time and part-time intervals over a period of 2 years. Their combined total effort was approximately equivalent to 12 to 16 months of full-time work for one person to assemble, digitize, and check historical data. Additional time on the part of senior researchers was spent in regular interaction with the junior scientists to answer questions and monitor progress. This time commitment by the senior researchers was significant but was not tracked. Finally, the data rescue effort was aided at various times by input from two participants in Operation Norman, D.G. Cook and R.W. Macqueen, who are retired but remain active as scientific volunteers at the GSC office in Calgary.

3.2. Methods—General statement

The following description of the methods employed to transfer historical field-observation data from hardcopy records to GIS files is an overview of the main steps involved. The GIS practices of the GSC for bedrock map data and interpretations, including the set-up and management of GSC geodatabases, are documented in detail in an unpublished internal report [32]. The organization of geological features in the ArcGIS environment into logical feature classes with suitable attributes is detailed in the Bedrock Data Model of the GSC [33], also an unpublished, internal report. This data model was used for the Operation Norman data rescue effort. Both internal reports can be obtained from the lead author upon request. Itemized here are the data capture processes used for



B

FEATURE	fossil locality
TYPE_ANAL	macropaleontology
SAMPLE	20-37
LITHOLOGY	not recorded
MAP_UNIT	Mount Kindle Formation
FOSSILS	echinoderms, cephalopods, corals
CATALOG_ID	C-003815
COLLECTION	GSC Calgary
STATION_ID	MQ-37
DISTANCE_M	20.7
YEAR_COLL	1969
REPORT	C-S-1 BSN 1970
REPORT_AGE	Late Ordovician
REMARKS	20.7-25.3 m above base; collected by Macqueen and Norford
REFERENCE	Fallas, K.M., and MacNaughton, R.B. 2014. CGM 97.
SOURCE_REF	Norford, B.S., 1970; GSC Paleontological Report C-S-1 BSN 1970.
MAP_ID	96D/SW

Fig. 5. GIS record of a fossil locality. (A) Measured section MQ-37 (red line) with associated fossil locality C-003815 (white diamond symbol). (B) Attributes of fossil locality C-003815 summarizing the paleontologist's report. In this case the STATION_ID of the fossil locality is populated with a measured section identifier because the fossil was collected while measuring a section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

field-observation stations, stratigraphic measured sections and fossil localities, and geological map interpretations. Although the details of this workflow are specific to capturing historical bedrock observations from a mapping activity, this or similar spatial geoscience data could be captured in other situations by adapting this workflow to any GIS software, using any suitable geometry (points, lines, or polygons) with a customized data model to record feature properties. The key factor is the ability to relate geological data or information to specific localities.

3.3. Methods—Data capture for field observation stations

1. An ArcGIS workspace and geodatabase was created for the area of interest in northwest Canada (see Section 2.2), an area of 41,847 km^2 (approximately 222 $\times$ 188 km). This area covers parts of two Universal Transverse Mercator (UTM) zones, and therefore required a custom Lambert projection to optimize distance measurements and present angular data accurately.
2. Using the ArcMap module, a view was created using the same custom Lambert projection. Base topographic shape files were projected and then added to the view, along with georeferenced satellite imagery (GeoTIFF files).
3. For each field-observation station record, the station was found on the 1:20,000 scale air photo from the Operation Norman collection (as recorded on the field-station data card, see Fig. 2) or on the corresponding 1:250,000 scale field map if the station could not be found on the air photo.
4. The corresponding position on the 2.5 m resolution satellite imagery or 1:50,000 scale topographic base in ArcGIS was located by visual matching and a station feature record (digital

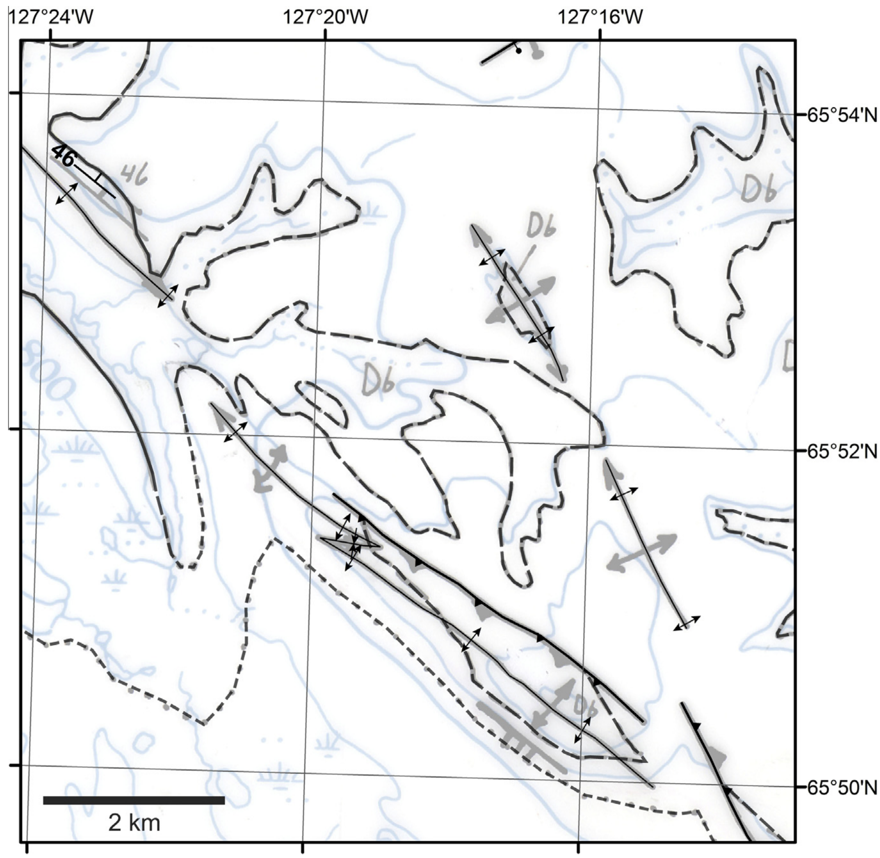


Fig. 6. Digitizing of geological map interpretation of Operation Norman map for part of NTS 96E [17]. On the scanned and georeferenced original, hydrography and topography appear as pale blue lines, geological interpretation appears grey. Digitized and symbolized features in geodatabase show as black lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

data point) was created at that location. The higher resolution of the digital imagery and digital topographic base allows for the recognition of the same geographic features seen in the source documents (compare Figs. 2 and 3), thus minimizing any error introduced by the digitizing process. Any introduced errors are estimated at 20–50 m, but may be as large as 100 m at locations where geographic features, such as stream banks, may have changed between the date of the air photo (circa 1950) and that of the satellite imagery (2008). To maintain unique records, station identifiers were derived from the year of observation, the geologist code, and the station number. This differs from the original station identifiers in the inclusion of the two-digit year (e.g. AC-486 in Fig. 2 vs. 69AC486 in Fig. 3).

5. Attributes to describe the properties of each field-observation station were then populated by manual entry, based on the information provided on the original data cards. In some cases, it was necessary to seek clarification from surviving Operation Norman scientists when the writing on cards was illegible or had faded, or when the original scientists had used unusual notations or abbreviations in their notes.
6. Separate records in customized feature classes according to the Bedrock Data Model used by the GSC [33] were then created for lithology descriptions, structural measurements, sample information, and associated photographs. Information from the data cards was entered manually for these features also (compare Figs. 2 and 3).
7. The related records were linked to the station point through the station identifier (STATION_ID), creating a suite of records to describe the variety of features recorded at each station.

3.4. Methods—Data capture for measured stratigraphic sections

1. Inclusion of measured sections in the project geodatabase was accomplished by finding the path of the measured sections on Operation Norman air photos or published maps, then digitizing the path into a feature class (Fig. 4). In some cases the entire path of the section was traced from a georeferenced air photo or map. In other cases, only the base and top of the section had been marked on the air photo, and so the section path had to be inferred from the position of annotations between those two points, along with consideration of the route most likely traversed to provide the highest quality, accessible exposure (e.g. along a ridge crest or stream bank). The magnitude of positional error introduced in the digitizing process is estimated at 50–100 m, and is likely to be significantly less for the end points of sections.
2. The attributes of the customized feature class allowed for the recording of basic information about each measured section: the section identifier or name; what stratigraphic units were measured; who made the observations; when the section was measured; coordinates of the base and top of the section; and a reference for any publications that include further details about that section. This information was entered manually from hardcopy records.
3. In cases where sections were sampled for paleontological studies, fossil localities were added as point features at each section and associated with the section through the section identifier.
4. Attributes populated manually from internal GSC Paleontological Reports and related publications included: a sample number and/or catalogue number; the stratigraphic

Table 1
Master Legend Table entries recording map unit information from published legend for National Topographic System map 96D [13].

Label	MAP_UNIT	MAX_AGE	MIN_AGE	Description
Qt-a_1390A	Quaternary	Quaternary	Quaternary	Alluvium, largely gravel
Te_1390A	Tertiary gravel	Eocene(?)	Eocene(?)	Gravel, conglomerate, sand, sandstone; minor coal and volcanic ash or tuff
Ct-le_1390A	Little Bear and East Fork formations	Late Cretaceous	Late Cretaceous	Sandstone, shale, minor coal
Ct-ss_1390A	Sans Sault and Slater River formations	Early Cretaceous	Late(?) Cretaceous	Shale, sandstone
Ct-b_1390A	Basal Cretaceous sandstone	Early Cretaceous	Late(?) Cretaceous	Basal sandstone and conglomerate
Dv-i_1390A	Imperial Formation	Late Devonian	Late Devonian	Shale, sandstone, minor limestone
Dv-c_1390A	Canol Formation	Late Devonian	Late Devonian	Shale, black, siliceous, bituminous
Dv-hi_1390A	Hare Indian Formation	Middle Devonian	Middle Devonian	Shale, minor siltstone and limestone
Dv-hc_1390A	Hare Indian, Canol, and basal Imperial Formations	Middle Devonian	Late Devonian	Shale
Dv-h_1390A	Hume Formation	Middle Devonian	Middle Devonian	Limestone, fossiliferous; minor shale
Dv-l_1390A	Landry Formation	Early Devonian	Early Devonian	Limestone, thick-bedded, resistant
Dv-a_1390A	Arnica Formation	Early Devonian	Early Devonian	Dolomite, brown, striped; minor solution breccia
Dv-ca_1390A	Camsell Formation	Early Devonian	Early Devonian	Limestone, massive, resistant; limestone breccia
Dv-b_1390A	Bear Rock Formation	Early Devonian	Early Devonian	Dolomite; dolomite solution-breccia; anhydrite, gypsum
SlDv-d_1390A	Delorme Formation	Late Silurian	Early Devonian	Dolomite, partly sandy, silty, argillaceous
OdSl-k_1390A	Mount Kindle Formation	Late Ordovician	Early Silurian	Dolomite, fossiliferous, siliceous; minor chert
CmOd-f_1390A	Franklin Mountain Formation	Late Cambrian	Early Ordovician	No description
CmOd-f4_1390A	Franklin Mountain Formation, "Cherty" member	Late Cambrian	Early Ordovician	Dolomite, chert, drusy quartz
CmOd-f3_1390A	Franklin Mountain Formation, "Rhythmic" member	Late Cambrian	Early Ordovician	Alternation of very finely crystalline dolomite with finely to medium crystalline dolomite
CmOd-f2_1390A	Franklin Mountain Formation, "Cyclic" member	Late Cambrian	Early Ordovician	Dolomite, conglomeratic, stromatolitic, and argillaceous, shaly
CmOd-f1_1390A	Franklin Mountain Formation, "Basal red beds"	Late Cambrian	Early Ordovician	Sandstone, red shales, conglomerate, dolomite, chert
Cm-s_1390A	Saline River Formation	Late Cambrian	Late Cambrian	Red beds; shale, siltstone, sandstone; salt, anhydrite, gypsum, dolomite
Cm-c_1390A	Mount Cap Formation	Early Cambrian	Middle Cambrian	Shale, thin-bedded limestone, sandstone, siltstone
Hl-g_1390A	Proterozoic gabbro	Helikian(?)	Helikian(?)	Gabbro, greenish black, medium grained
Hl-ld_1390A	Little Dal Formation	Helikian(?)	Helikian(?)	Dolomite and limestone, partly sandy, silty, and argillaceous; minor shale
Hl-5_1390A	Unnamed unit H5	Helikian(?)	Helikian(?)	Shale, partly red, nodular; limestone, dolomite
Hl-ku_1390A	Katherine Group, upper division	Helikian(?)	Helikian(?)	Quartzite, dolomite, shale
Hl-kl_1390A	Katherine Group, lower division	Helikian(?)	Helikian(?)	Mainly quartzite; minor shale and dolomite
Hl-t_1390A	Tsezotene Formation	Helikian(?)	Helikian(?)	Shale, sandstone, dolomite, local limestone; gabbro sills
Hl-1_1390A	Unnamed unit H1	Helikian(?)	Helikian(?)	Dolomite, minor chert

distance from the measured section datum; the map unit sampled; fossil type; reported age; and a reference to the GSC Paleontological Report or published paper (Fig. 5).

3.5. Methods—Data capture for Operation Norman map interpretations

To accompany the original observations from Operation Norman, the published map interpretations were also digitized into a dedicated dataset within our project geodatabase.

1. Good condition originals of published map manuscripts were scanned on a large format drum scanner. These originals were a combination of mylar sheets and paper copies that had been carefully preserved in a map cabinet by one of the original authors.
2. The resulting images, saved as TIFF files, were attached to ArcMap for georeferencing. Topographic features on the published map were matched to topographic features in the GIS files provided by Geomatics Canada. Georeferencing points were added until the positional error on the scanned map dropped below 250 m (equivalent to 1 mm on the original paper map).
3. Geological line features such as contacts, faults, and folds were then digitized by tracing the feature on the scanned map into the corresponding customized feature class (Fig. 6).
4. Attributes were assigned to each line in each customized feature class based on information provided about symbols in the legend of each published Operation Norman map.
5. ArcGIS tools were used to check for topological or attribute errors and any identified errors were corrected.
6. A map unit label point was placed in each area occupied by a map unit.
7. Using all the features comprising the map unit boundaries (e.g. contacts, map neat line), map unit polygons were then built from the digitized line work and the map unit labels. This step was easily repeated if errors were revealed and corrections required.
8. Properties of the map units recorded in the legends of the published Operation Norman maps were manually entered into a "Master Legend Table" along with the corresponding label—one record for each unique map unit on each map (Table 1).
9. Map unit properties recorded in the Master Legend Table were then added to the map unit polygons built in step 7. This was done by joining the Master Legend Table to the

map unit polygons on the basis of the map unit label, then using the 'Field Calculator' function in ArcGIS™ to copy the information from the table to the polygons. The main properties derived from the legend include the name of the map unit, the age of the unit, and its description.

10. An abbreviated reference to the original map publication (a source reference) was also included as an attribute for map unit polygons and line features to ensure that future GSC researchers will know from which publication these features were derived.

3.6. Methods—Data checking

In order to verify the usability of the digitized Operation Norman data, certain aspects were checked systematically for each field station: the completeness of the attributes; the accuracy of the attributes; and the accuracy of the location. The completeness and accuracy of the feature attributes was checked by comparison to original records for randomly selected stations, combined with basic queries in the GIS software to search for omissions or flaws in logic. For example, if an observation of a cliff-forming limestone was assigned to a map unit known to contain only recessive shale, the original notes were re-examined to determine the source of the error. Locational accuracy was checked by inspection against georeferenced images of the published Operation Norman maps. An additional review of the interpreted map unit at each station relative to map unit polygons revealed other potential digitizing errors, but in some cases these turned out to be errors introduced during the Operation Norman map compilation process. In the case of related field-station records, the links between station, lithology and structural measurement records were checked by joining the features using the STATION_ID, then looking for features with no joined record. Any omissions or errors introduced during the digitizing process were corrected with reference to the original notes.

Similar to the techniques used to check station observations, measured sections were checked for consistency with the Operation Norman bedrock map interpretations—i.e. the map units traversed by the line of section are the map units reported as having been measured. In cases where the digitized record did not match the bedrock map interpretation, historical notes were re-examined to identify and correct any digitizing errors. The digitized locations of fossil collections were also cross-checked with the position of any digitized stations or measured sections from which they were collected. Discrepancies were resolved on the balance of evidence from written coordinates, written descriptions, and locations marked on air photos or field maps. Data checking of geological line features (contacts, fault, folds, etc.) involved querying properties for accuracy and completeness in comparison to available Operation Norman legend information, and visual inspection relative to topographic features.

Digitizing and transcription errors not identified by the above techniques likely include typographical errors in written descriptions, particularly for lithology observations, and information that might have been omitted during the data capture process. Both types of errors are difficult to identify using GIS queries, and a comprehensive identification of the errors would likely require comparison of each digitized record with the original documents by a scientist familiar with this type of data. However, ongoing use of the data increases the likelihood of closer inspection of digitized records, and will identify typographical errors as opportunity arises.

The subsequent field work provided additional opportunities to evaluate the scientific accuracy of the original Operation Norman data by revisiting selected sites and comparing new observations to the historical records. Another technique involved visiting new sites that lay geographically between historical mapping stations, and then attempting to correlate features along strike. Field checking showed the Operation Norman station and measured section observations to be highly reliable, even in areas where the map interpretation subsequently has been revised.

4. Results

4.1. Overview

The efforts expended on the rescue of Operation Norman data are well justified by the contribution these data made to the outcomes of the Project. Most fundamentally, the rescued data have been incorporated into 14 new bedrock geology maps at 1:100,000 scale [34–47]. However, they also have contributed to new or revised lithostratigraphic classifications [48–51], new paleogeographic interpretations [51,52], and new tectonic interpretations for the Project area [53]. In the following sections, we summarize the chief pathways by which the rescued data contributed to Project success: as a reliable data source to increase data density; as a means of recognizing sites requiring focused study; and as a source of serendipitous outcomes.

4.2. Historical field observations as a reliable data source

The rescue effort focused on historical Operation Norman data was intended to further the main goal of the Project: publishing new map interpretations, with supporting observational data provided in GIS-format files. The effort to incorporate historical observations—including station locations, lithology descriptions, structural measurements, measured-section locations, and fossil localities—in new map publications was successful. Out of a possible 434 historical field stations within the study area, 410 were successfully located within an acceptable margin of error (typically less than 100 m) and digitized into the geodatabase used for map compilation (94% success rate). The 410 digitized locations included associated lithology descriptions (599, reflecting the presence of more than one rock type at numerous localities) and structural measurements (248). The quality of the hardcopy records allowed for the transcription of descriptive details into the GIS system, with only minor data loss due to fading or illegibility. The existence of photographs, sketches, or samples, where noted on the field-station record cards, was recorded in the geodatabase, but time and resource limitations did not permit us to incorporate these data further in the data rescue activity. Locations and basic information for 51 measured stratigraphic sections also were captured as features in the project geodatabase. Cross-referenced with stations and measured sections in the geodatabase were 264 records of paleontological assessments, of which 247 yielded identifiable fossils.

Operation Norman data are presented with newer field observations and new map interpretations in recent GIS map publications from the Project [34–47]. On the final versions of the Project's maps, Operation Norman data accounted for 21% of the total of 1816 field stations (Fig. 7), 25% of the 2287 lithology descriptions, 19% of the 1227 structural measurements, 36% of the 135 measured sections, and 35% of the 668 fossil locality records. Data coverage within the new maps was significantly increased by these archival data points, without the need to re-examine many sites documented by Operation Norman geologists. Such sites needed only selective spot checking, which showed Operation Norman observations to be highly reliable (see Section 3.6). As a result, considerable time was freed for more detailed study of areas with problematic structural or stratigraphic relationships (see Section 4.3).

It may be noted that the interpreted geological features from the Operation Norman map publications have been preserved as GIS features for reference in archive files of the GSC, but were not used in recent map compilations. The new map interpretations only incorporated the historical observations of Operation Norman.

4.3. Historical field observations as an aid to identifying data anomalies

Because Operation Norman was carried out at reconnaissance scale, mappers on the project did not have the luxury of studying complex geology in detail, nor of revisiting localities to resolve apparently contradictory data. As a result, it was necessary in some cases to provide what they considered to be the most defensible interpretation on their published maps, but hard copy maps inevitably hide some or much of the complexity that may exist in the data that inform geological interpretations. Additionally, at the time of Operation Norman there were significant gaps in the understanding of the stratigraphy of the eastern Mackenzie Mountains, perhaps most markedly with respect to Proterozoic formations; compare, e.g., the treatment of Proterozoic units by Aitken et al. [22], based on Operation Norman, with that of later reports by Aitken et al. [54] or more recent work by Turner and Long [55]. A benefit of the rescue of Operation Norman data was the identification of anomalous or otherwise problematic data points, which served to point Project field parties to sites needing detailed study.

Fig. 8 shows an area in the eastern Mackenzie Mountains that shows the value of anomalous historical observations. The only Operation Norman outcrop station in this area appeared to conflict with the published map interpretation (Fig. 8a; [13]). During field work in 1969, the geologist recorded the presence of sandstone that contained possible trace fossils. During map compilation, the outcrop was assigned to the informally named 'H5' unit, tentatively considered to be of Mesoproterozoic age (Helikian in the GSC's usage of the time: 1640–880 Ma). However, based on that age assignment, the 'H5' unit must have predated the appearance of infaunal burrowing by hundreds of millions of years [56]. It is not certain whether the decision to assign the putatively burrowed sandstone to a Mesoproterozoic unit reflected uncertainty around the identification of the burrows, uncertainty regarding the stratigraphic record of burrowing organisms, or another reason. During our work, a record of possible trace fossils in an outcrop assigned to the Mesoproterozoic was sufficiently anomalous to catch the attention of Project participants. In seeking to evaluate the historical observation, numerous nearby outcrops were visited (Fig. 8b). This verified the presence of trace fossils in the sandstone and led to the discovery of trilobites that place these exposures in Cambrian Series 3 (Middle Cambrian). This and other new observations in the area, spurred by the apparent data anomaly, led to the recognition of structural complications involving both Proterozoic and Cambrian strata, and a significant revision to the map interpretation [40]. It is to the credit of the geologists of Operation Norman that they not only recorded data that supported their interpretations, but also preserved anomalous data that would later point out the need for revisions to their work.

4.4. The serendipity factor

The data rescue effort described herein was done in support of bedrock geological mapping within the geographic bounds of the Project area. However, the exercise also contributed serendipitously to a clearer understanding of regional lithostratigraphy. During the mapping, it became necessary to define a new Cambrian map unit (Nainlin Formation; [51], but this unit extended beyond the bounds of our mapping area. Because we were aware of the breadth and quality of Operation Norman's data coverage, we could seek out archival mapping stations and stratigraphic sections to use as control points on the unit's distribution, thickness, and variations in lithology.

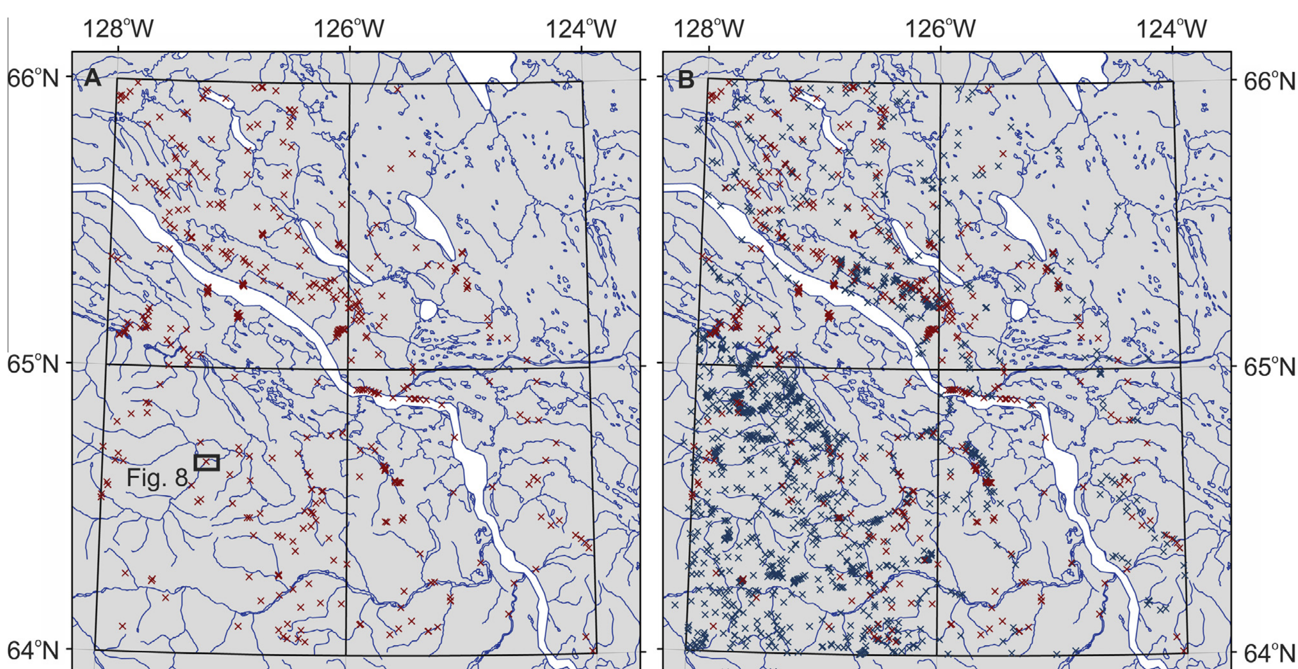


Fig. 7. Distribution of historical and modern data; see Section 4.2. (A) Area of data rescue showing the distribution of Operation Norman field observation stations (red crosses). Outline of area shown in Fig. 8 is shown. (B) Operation Norman stations (red crosses) combined with recently collected data (blue crosses), showing how recent work concentrated on areas with sparse coverage during Operation Norman. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

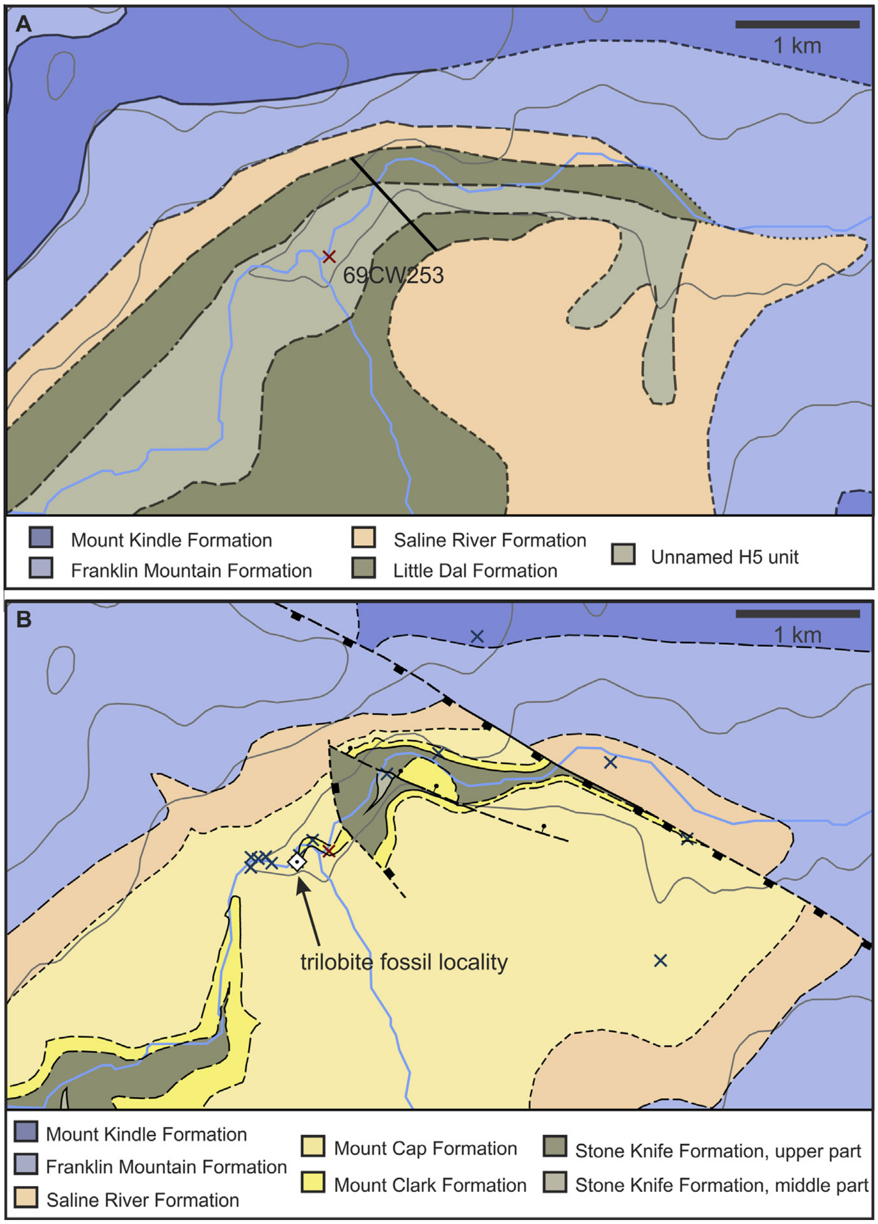


Fig. 8. An example of historical data guiding new research; see Section 4.3 for discussion. (A) Operation Norman map interpretation [13] showing location of sandstone outcrop containing apparently anomalous trace fossils (station 69CW253); map units in key reflect Operation Norman terminology. (B) New map interpretation [40], developed after discovery of Cambrian trilobite fossils during investigation of outcrops (blue x symbols) around station 69CW253; map unit terminology reflects current usage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Ongoing efforts to compile archival data also encouraged publication of an archive of unpublished data from an Operation Norman stratigrapher, the late J.D. Aitken. This consisted of hand-drafted stratigraphic sections, many with descriptive notes, for several Proterozoic formations. These were measured in the 1970s and 1980s as Dr. Aitken investigated stratigraphic issues recognized during Operation Norman. Some of these sections were unpublished and others had been published only in part. High-resolution scans of the sections, accompanied by an explanatory report, were published by the GSC [57]. Although the scans are not machine-readable, the publication put an important data source into the public domain, in conjunction with the Operation Norman data rescue operation. These data influenced a long-overdue formalization of Neoproterozoic lithostratigraphy in the eastern Mackenzie Mountains [49,50].

It is said that chance favours the prepared mind. We suggest that a similar relationship exists between serendipity and data rescue operations. Rescue efforts focused on a particular data set or area, in addition to meeting immediate goals, may increase the awareness of unexploited data sources. Even if such sources are not the subject of full-scale data rescue at the time, they can be exploited selectively or flagged for more detailed attention in the future.

5. Discussion

5.1. Data accessibility, usability, and sustainability: before and after

Prior to 2013, Operation Norman data for the Project area could be accessed only by GSC staff, or by visitors to the GSC office in Calgary, with the exception of the small subset of data that had been included in published maps and reports. Maps recorded good scientific work at reconnaissance scale but did not display all data. Being mainly hand-lettered, black-and-white manuscript maps, they generally did not display the data to best advantage.

Usability of the published data was limited, as it existed in hard copy only. The systematic organization of the archived Operation Norman data ensured that nearly all data resided together in a single location, as a well-organized set of hard-copy records. But knowledge of the design and contents of these records was restricted to a few surviving project participants, all of whom had been retired for more than a decade by the time the rescue project began. Although the Operation Norman data had been placed in safe storage, their preservation in hard copy presented a number of challenges to sustainability. Prior to 2010, the GSC-Calgary office lacked a sprinkler system for fire suppression, and thus there existed the danger of loss of research materials to fire. After high-volume sprinklers were installed that year, the primary danger became water damage. Concerns also existed about damage to materials by vermin, paper yellowing and becoming brittle with age, and pencil lines fading on maps and field notes. Corporate knowledge of Operation Norman existed only among retired colleagues, or among former GSC employees.

Following the data rescue operation, over 90% of the original Operation Norman field observations for the Project area have been located, successfully brought into a GIS system, and published as a component of new map interpretations (see Section 4.2). These observations help constrain the new map interpretations and can be queried and analysed along with observations collected between 2009 and 2012. Their inclusion in recent GIS-enabled map publications makes the details of these observations available to the public for the first time. Currently, free public access is available by downloading individual publications through NRCan's GeoGratis website (see Section 3.1). Additional access through web services is under development. By rescuing the data and capturing it as GIS features, it is anticipated that the data will continue to be preserved in digital form within digital archives of the GSC, along with the hardcopy records. The archive structure of the GIS data and interpretation is set up on networked drives internal to NRCan. The archives can be accessed from multiple desktop terminals at any office of the GSC, and the archives are backed up at regular intervals. The long-term preservation effort includes maintaining information about the lineage of data (a component of metadata), and for that reason an attribute is included with the historical data that identifies it as coming from Operation Norman records and/or from a published map resulting from Operation Norman activities.

5.2. Challenges encountered during data rescue

During our Operation Norman data rescue effort, challenges fell into two categories: (1) difficulties in understanding the written field-station records and (2) difficulties in identifying a location for a field-station record. Written records were challenging to work with in cases where the writing had faded on the card, notes were made in an illegible hand, or the original observer used abbreviations, in some cases known only to them. For the junior scientists who carried out the data entry, these problems often could be overcome by consulting one of the retired Operation Norman geologists or one of the senior scientists supervising the data rescue activity. In this manner most of the observation details recorded on the data cards were entered into the attributes of the GIS features.

Problems identifying field locations accurately can make or break the value of archival data. It is essential that data be associated with a location on the surface of, or within, the Earth, for reasons clearly stated more than 150 years ago by the founder the GSC:

> Unless you know the geographic position of every rock exposure that comes before you, you cannot tell the general relations of the whole, and you cannot make the physical structure of a district intelligible to yourself or to others. Without geographical position, the dip and strike of a rock are worth nothing, and the occurrence of a valuable mineral in two localities distant from one another are just two isolated and unrelated facts.
>
> Sir William Edmond Logan, 1855
>
> Reporting to the Select Committee on the Geological Survey of Canada

Whereas partly indecipherable field notes may still yield useful data, data that cannot be accurately located are of limited value, and in the context of moving data into GIS systems, cannot be rescued. Thus, a significant portion of time during data rescue was dedicated to assigning observations to accurate and precise locations. Location difficulties were encountered when a field station had not been marked or labelled properly on an air photo or field map. Such difficulties typically could not be resolved, resulting in exclusion of these records from the geodatabase. Measured sections present similar difficulties regarding reliable location information [58], and thus sections in the Operation Norman dataset that were located graphically on an air photo or field map were most likely to be rescued.

5.3. Data rescue as a contribution to reuse of data

The expenditure of time and resources spent in data rescue efforts such as this can be significant (see Section 3.1). However, a key driver for data rescue is the goal of reusing data, thereby reducing costs and avoiding unnecessary replication of effort [59,60]. If spot-checking during data rescue suggests that data gathered by earlier workers generally are reliable (see Section 4.2), then it should not be necessary to restudy sites those workers documented, except in cases of apparent anomalies (see Section 4.3). The rescue of Operation Norman field observations described herein was undertaken to expand the dataset of publicly available geological observations in the Project area and to improve the breadth and density of observation. As a result, historical Operation Norman data, along with newer data generated during the GEM program, are readily available to future researchers in the central Mackenzie Valley region to draw on to investigate new scientific concepts, without the necessity of mounting a large field program to re-generate suitable field observations. Future projects will be able to accomplish more with smaller, targeted field programs. Reuse of geospatially referenced, rescued data can lead to significant cost savings, either by obviating the need to revisit sites, or by ensuring that sites can be found efficiently, without unnecessary time spent searching. This is particularly true in isolated regions, where access costs may be prohibitive. Reuse becomes essential in instances when bedrock exposures are destroyed (e.g. quarrying or mining), covered over (e.g. flooding resulting from damming of rivers, urban development, etc.), or otherwise rendered inaccessible.

By contrast with scientific disciplines that use historical data to identify trends through time, such as climatology, e.g. [61] or fisheries science, e.g. [62], bedrock geological mapping is concerned with geological relationships that typically do not change during the time-frame of human observations. As a result, historical field observations can usually be combined with modern observations to describe and interpret the bedrock geology of an area. What can change, sometimes radically, are the theoretical understandings that may inform or influence the compilation of bedrock geology maps [63]. Rescued data that are put in proper geospatial context (see Section 5.2) become reusable [58,59]. The end-users then can interrogate the data that underlie a published map and draw their own conclusions regarding the validity of the interpretations presented by the map's compiler. (From this perspective, it is noteworthy that the Operation Norman and GEM mapping efforts came to similar conclusions regarding large-scale bedrock geology trends, despite being separated by four decades. This suggests that conclusions reached by Operation Norman geologists generally were reproducible.)

6. Future work

During the first phase of the GEM Program, we were able to incorporate Operation Norman field data into a number of publications (see Section 4.1). This success has encouraged us to revisit the remainder of the Operation Norman data during the second phase of the GEM Program. We intend to apply the same data rescue process over a broader geographic region in support of new research. The available materials exist in a similar condition to those already rescued, and a similar result is anticipated. A strong motivating factor is the desire to accomplish this next rescue phase while scientists involved in Operation Norman remain available for consultation, and before the hard-copy materials suffer any damage. For this second phase of data rescue, our approach has expanded to include information about the thickness of stratigraphic intervals (map units) recorded in descriptions of measured sections. This information is being extracted from original field notes and published summaries derived from Operation Norman field activities. Thickness information tied to precise locations will allow for improved geographic analysis of the distribution of map units without having to revisit each of the historical sections to re-gather the data.

7. Conclusions

1. Data rescue of historical records is a preventative step to avoid loss of value to the greater scientific community and the public that might result from the physical deterioration of the records with time. Within the region of Operation Norman for which data rescue was undertaken, more than 90% of archival, hard-copy observation records are now archived in a corporate database. The rescued data also are available for free public download. As part of a new GSC project, the procedures for effective data rescue described in this paper are now being applied to the remaining Operation Norman data.
2. Input from original participants in Operation Norman was an important aid to effective data rescue. Because they were familiar with the historical work, they were an important resource for establishing the nature, content, and organization of the historical data and information.
3. In the context of bedrock geological mapping, historical records can be rescued by transfer to a GIS environment, but this is possible only if they can be associated with an accurate and reasonably precise location. Research materials from Operation Norman had been carefully curated, and most field observation records were clearly tied to locations marked on air photographs or topographic maps. This ensured the accurate association of these observations with correct locations.
4. As a result of the data rescue effort documented herein, a geographic subset of historical data collected by Operation Norman now exists in electronically accessible formats in the public domain, and can be manipulated, queried, or analysed. This respects the principals of open data, and contributes to the completeness of the scientific record, thereby augmenting scientific analysis and contributing to future decision making, reduced repetition of effort, and effective use of public funds.

Acknowledgements

The data rescue effort documented in this paper was funded by Natural Resources Canada (our employer, and a department of the Government of Canada) as part of the first phase of the Geo-mapping for Energy and Minerals Program, 2008–2013. Preparation of this report was done as part of the second phase (2013–2020) of the same program. As part of Natural Resources Canada, managers within the Geological Survey of Canada influenced the timing and geographic focus of this study, but did not influence the research approach, the collection of data, subsequent analysis, or the writing of this report. We owe our thanks to Don Cook and Roger Macqueen for guiding us through the Operation Norman records and generously sharing their knowledge of the original work. The diligent efforts of N. Raska and K. Montgomery in the data rescue activity are gratefully acknowledged. This report benefited from a GSC internal review by L. MacDonald, and from journal reviews provided by two anonymous referees. This is Earth Sciences Sector Contribution 20140261.

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